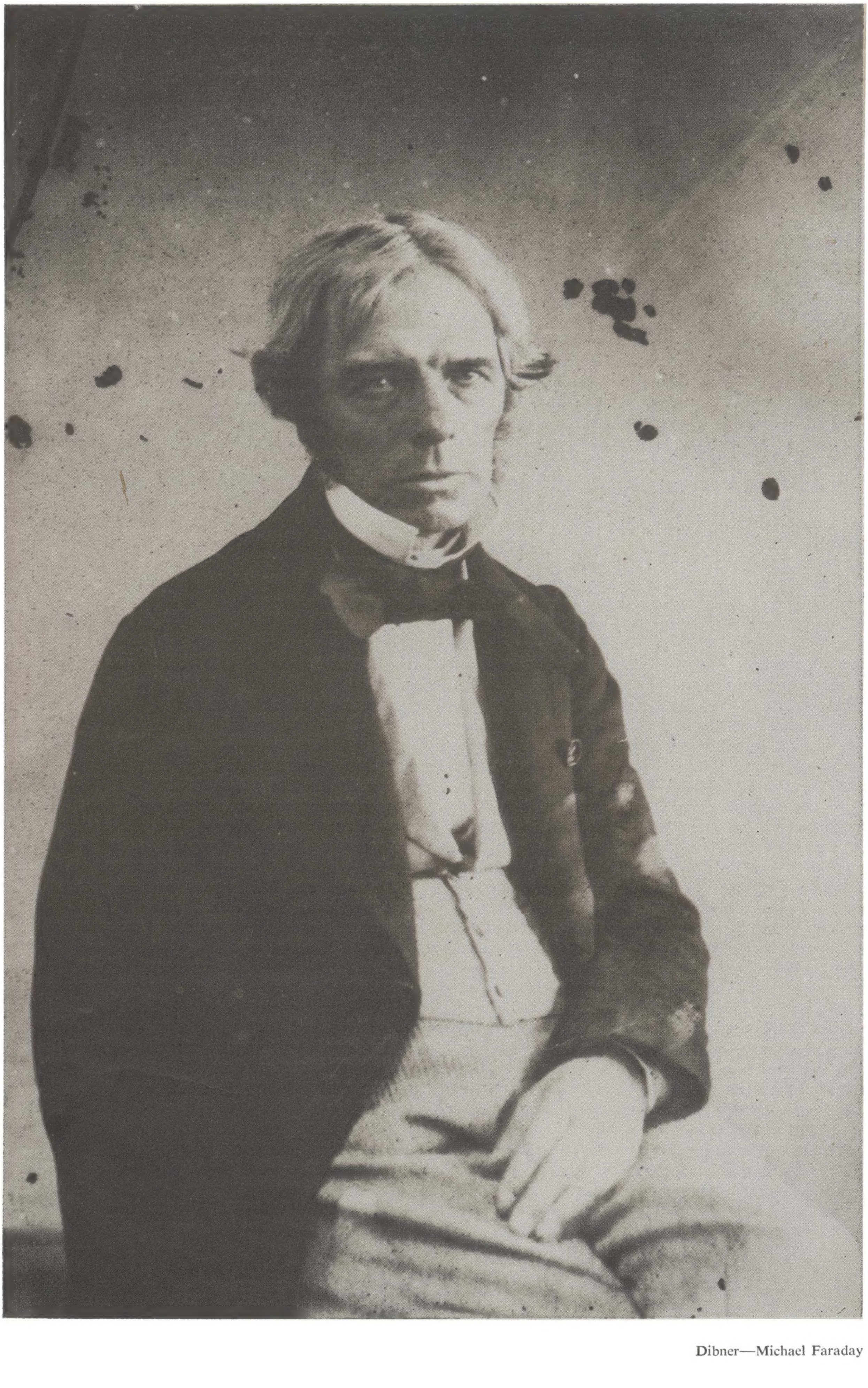


Michael Faraday—a centennial

On this hundredth anniversary of the death of Michael Faraday, we are again reminded of our debt to the genius whose discovery of electromagnetic induction in 1831 was the beginning of a new era in mankind's development—the Electrical Age

Bern Dibner *Burndy Corporation*

Beyond his own material contributions to the electrical art, Faraday's experimental approach and intuitive resolutions opened channels of inquiry into which his successors moved. Thus his bequest to society has increased in value far beyond that which he himself could have envisioned. In this article commemorating the centennial of Faraday's death, we follow him from his humble beginnings as a simple bookbinder's apprentice until he quietly passes into history at the age of 76—the leading scientist of his generation.

A hundred years ago, on August 25, 1867, the weary heart of Michael Faraday stopped beating. At the end, he just sat quietly in his chair, his faculties spent, his awareness of his surroundings gradually reduced to zero. Thus the leading scientist of the first half of the 1800s passed into history. He had found the peace that he was awaiting when he wrote to his friend Auguste de la Rive, in 1861, "and there is the rest for those who like you and me are drawing near the latter end of our terms here below." He died, as he had lived, with absolute modesty, avoiding every ostentation and denying all pomp and honors. His funeral was of the simplest, held in privacy. His grave in Highgate Cemetery bears simply his name and date of birth and death. He had rejected titles, pension, and burial in Westminster Abbey.

The same intelligence that had revealed to this blacksmith's son the important laws of nature that he and his successors wove into the great electrical networks of today had also taught him that his heritage did not lay in impressive monuments. Instead, he left a series of observations in physics and chemistry that were to guide research for most of the coming century. He had won a following among the scientists and scholars of the great universities, in the research laboratories, and in the shops and industries created from his discoveries. He had founded the electrochemical industry, had established an important branch of metallurgy, and had provided guidance in the ways of research by an extraordinary series of published experiments. His lectures at the Royal Institution in London set a pattern for disseminating the progress in the physical sciences, thereby attracting the support of the flourishing industries of Victorian England. Only half a century spanned the announcement of Faraday's most important discovery—electromagnetic induction—and its application as a central station generating and distributing network.

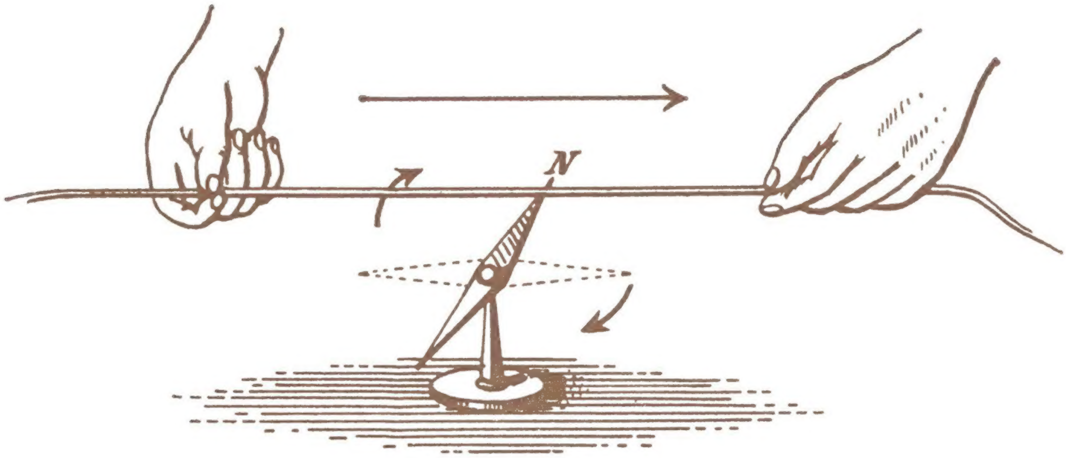
THE AGING Faraday is shown in an exceedingly rare photograph found recently in Paris. Having risen from bookbinder's apprentice to the foremost scientist of his time, he shows here the stresses of his dedicated life.

Three important steps

Three discernible steps have elevated the electrical science from the oblivion of the past to its present position of primacy of man's energy forms. The first of these was the formation in 1600 by Dr. William Gilbert of London of the known electrical behavior of his time. His important book, *De Magnete*, summed up the magnetic knowledge so urgently needed by the explorers and navigators of the early 1600s. The book also contained a chapter on electricity, a science which evolved through the electric machines of Otto von Guericke and Francis Hauksbee that made electrical experimentation dramatic and popular. It was Franklin and van Marum who pushed elementary electrostatics to the limits of its development.

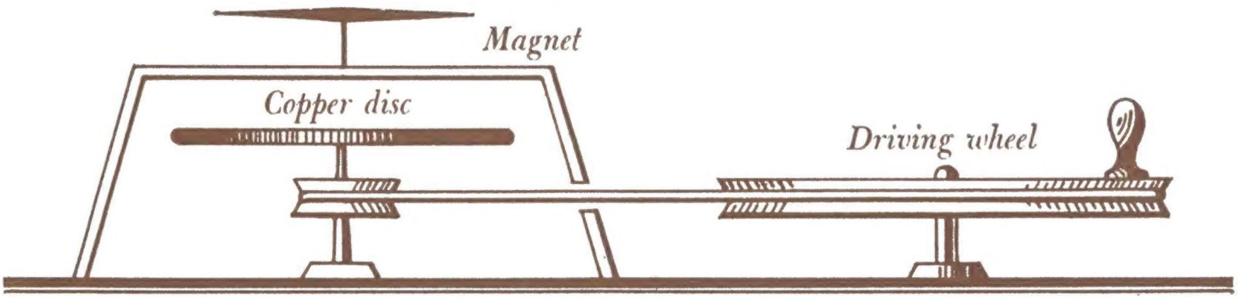
It remained for Alessandro Volta to introduce a second form of electric generation (by chemical means) with the discovery of his voltaic pile. His primitive electric battery provided a continuous source of electrical flow that opened ways to illumination by the electric arc, electroplating, and the dissociation of water into oxygen and hydrogen. But most important, Sturgeon's construction of an electromagnet, in 1825, provided the lead for the electric telegraph. This was the first wide application of electricity, but the energy for it came from voltaic batteries. Broad electrical development depended on a different energy source—the electric generator, and later, the transformer. These developments stem from the genius of Faraday.

The era that was opened with the introduction of Volta's battery in 1800 remained comparatively quiescent during its first two decades. In 1820 H. C. Oersted in Copenhagen announced a singular discovery; he had observed that

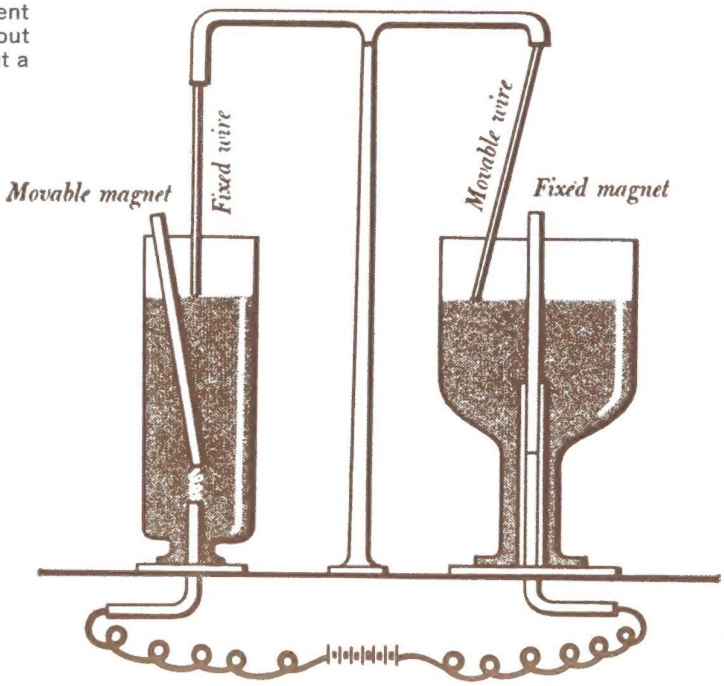


WHEN Oersted passed a voltaic current through a wire he noticed that a magnetic needle set itself transverse to the wire.

ARAGO caused a magnetic needle to drag after a revolving copper disk, but he did not explain the action.



IN FARADAY's first famous experiment a magnet was made to revolve about a conductor and a conductor about a magnet.



a wire carrying an electric current had a magnetic field generated around its length. This startling announcement set off investigations in many laboratories and especially stimulated Ampère in analyzing the electromagnetic forces in adjacent conductors. The great holding power of an electromagnet turned the keenest minds of Europe and America toward further experimenting and calculation. They faced the obvious challenge: if such intense magnetic fields could be developed from an electric solenoid, why could not the process be reversed? Why could not electricity be generated from magnetism? Between 1820 and 1831 Faraday alone had made four extended efforts to convert magnetic energy into some electrical form, but without success. His triumph in 1831 was the commencement of the Electrical Age.

The early years

In an England that accepted strata in society, Faraday never forgot his humble beginnings. Born on the outskirts of London on September 22, 1791, his father was a working blacksmith, a trade which was also followed by his brother. Michael's early schooling was very elementary and at the age of 13 he became apprenticed to a bookbinder and bookseller in London. This choice of occupation was fortunate for Michael because he not only learned to bind books, but made the time to read them during the eight years of apprenticeship. He learned of the marvels of electricity from the *Encyclopedia Britannica* and about chemistry from Mrs. Marcet's *Conversations on Chemistry*. Both disciplines led to experiments with such apparatus as he could acquire with his very slender wage. He constructed an electrostatic machine and in 1812 he built a voltaic pile. It was then that Faraday learned of lectures being given in chemistry in London and he borrowed funds from his brother in order to attend them. While carefully listening and observing the experiments, he made many notes and illustrations. These he transcribed and assembled into four volumes, which he bound and presented to his sympathetic and intelligent employer, George Riebau. A visiting patron of the bookshop was so impressed by the notebooks that he invited young Faraday to accompany him to a Friday evening lecture at the Royal Institution on Albemarle Street in London. The speaker was the director of the laboratory of the Institution, Humphry Davy, and the occasion left a profound impression on the lad. During the day of the third of the four lectures attended by Faraday, the excitement was heightened by the conferring of knighthood on the lecturer, thereafter known as Sir Humphry Davy.

When his term of apprenticeship was over, young Faraday applied to Sir Humphry for employment at the Institution and, in December 1812, as a measure of his interest, he sent bound copies of the notes he had made during Davy's four lectures. In the following March, Faraday was hired for 25 shillings a week as a laboratory assistant—and thus commenced the fruitful association of the two great minds that were to fashion so much that was new in the sciences. In October 1813 they embarked on an 18-month journey to the Continent, returning home in April 1815. In spite of the disturbances of the Napoleonic wars, Davy's international reputation made it possible to cross frontiers without difficulty. He and Faraday, his general assistant, visited the laboratories and talked to the savants of Europe. Calls were made on such famous scientists as Ampère, Chevreul, Humboldt, and Gay-Lussac. Prior to this visit, Faraday, now 22 years old, had never been farther than 12 miles outside of London; he now faced and talked with the men whose books and papers he had so avidly read. A high point of their visit to Italy was a meeting with Count Alessandro Volta, who was dressed in the formal uniform of the Court. The contrast between this eminent figure and the erstwhile bookbinder's apprentice was not lost on the sensitive young man.

Another impressive visit was to Count Rumford, with whom Faraday dined at his home near Paris. The Count's interest also spanned physics and chemistry but he had acquired yet another distinction. A colorful American (born Benjamin Thompson at Woburn, Mass., in 1753), Rumford had founded the Royal Institution in 1799. As a veteran of the American Revolution (on the Tory side), he had seen all of Europe in revolutionary turmoil, and he had observed, as had others, that science was to be an offspring of that revolutionary age. To promote the interests of science, Rumford had established the Royal Institution as essentially a "learned society" whose purpose was "diffusing the knowledge and facilitating the general introduction of useful, mechanical inventions and improvements, and for teaching, by courses of philosophic lectures and experiments, the application of science to the common purposes of life." At that time, "philosophical" meant broadly "scientific" and Faraday always preferred to be called a philosopher rather than a physicist. The Institution differed from the Royal Society in that it was mainly concerned with organized experimental research rather than with acting as a clearinghouse for the reports of its members and affiliates as did the Royal Society.

At the lectures held at the Royal Institution a platform was provided for the man of science and engineering—the chemist, electrician, physiologist, geologist, or mineralogist—to present a new approach, a novel theory, or a promising experiment. In addition to the thrice-a-week afternoon courses, there were the six lectures for juveniles at Christmas time and the more formal Friday night discourses. By explanation, illustration, and demonstration, the world of science came to witness the work of Davy, Faraday, Brande, and later Tyndall and Dewar. The Christmas series was especially prepared by Faraday for boys and girls and was given for 19 Christmas seasons. Having had no children of his own, this provided a special outlet for his generous personality.

Faraday remained at the Royal Institution for 54 years and in his time published 158 papers. His greatest monument, *Experimental Researches in Electricity*, appeared in 29 series of papers gathered and published in three volumes after their appearance over a span of 27 years. For his work he was awarded more than 100 academic and scientific honors, including degrees, medals, orders, and other marks of distinction. He actively sought only Fellowship in the Royal Society but he declined its presidency, as well as a knighthood and a pension. He never applied for a patent and preferred to "remain plain Michael Faraday to the last." Although he had no training or ability as a mathematician, he was a founder of one of the most exacting of sciences—electricity—but channeled his research through experiment. His interest in the sciences was very broad, involving him in chemistry, geology, metallurgy, mechanics, optics, acoustics, heat,

magnetism, and electricity. It was this breadth of interest that made him intuitively recognize the conservation of energy and its transformation into various forms. It was this drive that stimulated him to hunt for, and finally find, a means of transforming magnetism into electricity.

His greatest discovery

The events that led to Faraday's most important discovery—magnetoelectricity—stemmed from a chain of earlier observations and theories by contemporary electricians. Davy, primarily a chemist, opposed Volta's theory of electric generation in the pile as merely the contact of dissimilar metals by proving that a chemical change took place in the battery elements of copper and zinc or of silver and zinc, and the electrolyte between them. Oersted's simple but critical link of magnetism to electricity has already been mentioned. On learning of Oersted's discovery, Davy and Faraday repeated the experiment and verified the results. A magnetic needle now became an indicator of the direction of flow of a current in a wire. Ampère's experiments with the dynamics of current-carrying wires became the quantitative basis of investigation. Arago, in France, magnetized iron bars by inserting them into energized solenoids and thereby produced "artificial" magnets. He also caused a copper disk to spin on its center and noticed that a magnetic needle positioned over the disk tended to be dragged by the disk, but for unexplained reasons. Joseph Henry, in the United States, improved electromagnets to the point where one could support a weight of nearly a ton. These novel results of research into electromagnetic relationships stimulated Faraday to shift his major interest from chemistry to electricity. Henry had independently discovered the principle of induced current (hence the *henry*, unit of inductance), but he credited Faraday with priority for the discovery because the latter had published earlier. Henry visited Faraday during his stay in England in 1837.

The first fruit of his intense investigation appeared in 1821 when Faraday demonstrated electromagnetic rotation. In a brilliantly devised setup he showed how the same electric current could cause a magnet to move about a fixed conductor and a conductor to move about a fixed magnet. His apparatus consisted of two glass vessels partially filled with mercury, with a fixed wire in the first and a magnet in the second vessel. About the fixed wire there was pivoted a movable magnet and about the fixed magnet in the second vessel was suspended a movable wire, its lower end dipping into mercury. When current was fed to the fixed wire, the movable magnet began to rotate, and concurrently in the second vessel the movable wire rotated; both motions continued as long as current flowed. This impressive experiment greatly expanded Faraday's reputation and in 1824 he was nominated by his friend Richard Phillips for membership in the Royal Society.

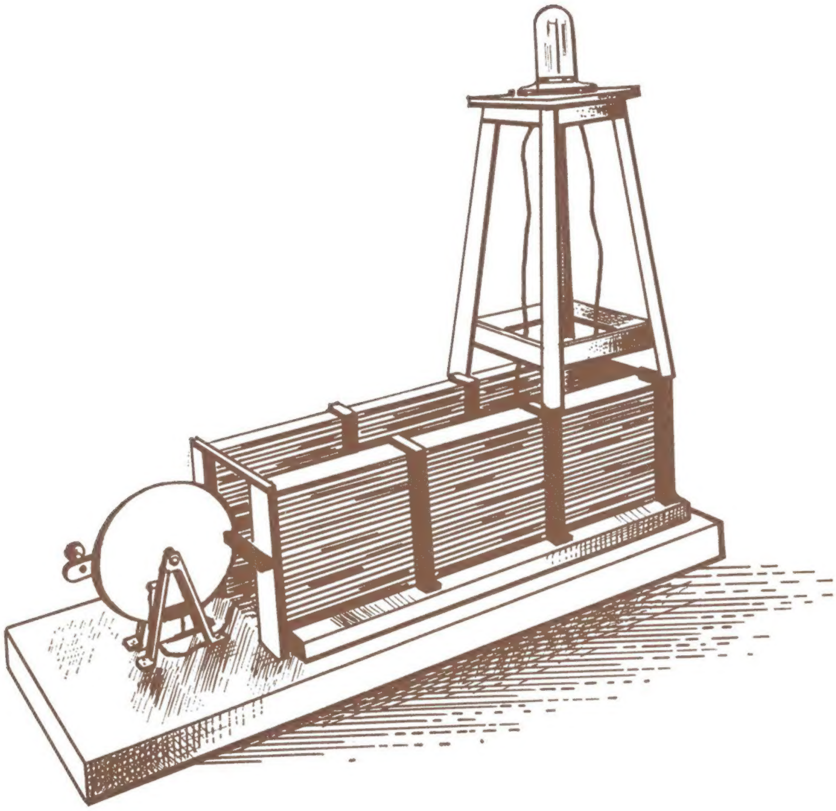
During the ten years from 1821 to 1831, the desire to demonstrate the successful generation of electricity from a magnetic source remained constantly with Faraday. He was now in full manhood, 40 years of age, and a correspondent with the foremost experimenters in England and on the Continent. He read and followed promising leads toward his goal, but nothing came of them. He was aware that electro*static* induction had been investigated and described during the previous century, but the constant-flow voltaic current could not be made to induce a similar current in a nearby wire. In an 1824 experiment Faraday had placed a bar magnet into a round copper wire coil but noticed that no electricity was produced. Other experiments proved equally fruitless, yet he was convinced that by the interplay of forces some process converse to that discovered by Oersted must be possible, and he was determined to find it. Other experimenters—Ampère, Arago, de la Rive, Herschel—tried disks, coils, and wires, but none struck the conclusive note.

In the summer of 1831 Faraday began his fifth series of investigations by making a soft iron ring some 15.2 cm in diameter. He then wound a coil of insulated copper wire on half of the ring's circumference and on the other half he wound a second coil. Upon connecting the first coil to a battery and the second coil to a galvanometer, he noticed a swing of the galvanometer needle, but it immediately returned to the zero position. However, when the connection was opened, a similar swing in the opposite direction was noted. Faraday linked the behavior of the galvanometer in his ring and coil experiment with the drag of the magnetic needle in Arago's experiment. He repeated the Arago experiment, observing the interaction of the needle's magnetism with the disk's magnetism created by the induced current. This resolved the problem in his mind.

From August to November 1831 Faraday carried on an intensive investigation of electromagnetic effects involving a series of simple but telling experiments in which he proceeded step by step toward the tantalizing problem. On September 23 he wrote to his friend Phillips: "I am busy just now again on Electro-Magnetism, and think I have got hold of a good thing, but can't say; it may be a weed instead of a fish that after all my labour I may at last pull up. I think I know why metals are magnetic when in motion though not (generally) when at rest."

Faraday's clinching experiment was performed on October 28, 1831, in which he reversed the relative motion of conductor and magnet. He did this by placing a 30.5-cm copper disk between the pole pieces of the great permanent magnet belonging to the Royal Society. The disk was provided with a crank and bearings so as to rotate easily. A metal collector rode on the periphery of the disk and another collector rode on its axle. Wires from the collector strips were led to a galvanometer. When the disk was revolved the galvanometer needle was deflected; when it was revolved in the opposite direction, the indicator needle was reversed. Faraday visualized the disk in motion "cutting" the magnetic lines of force across the magnet's poles. In ten days of intensive work all the questions arising in his mind were resolved. On November 24 Faraday read a memoir before the Royal Society. This was supplemented by a detailed letter to Phillips sent from Brighton on November 29 in which the exhausted Faraday gleefully reviewed his success and projected further exploitation of his discovery. The substance, he wrote, was that "currents of electricity are formed in the direction of the radii; continuing, for every simple reason, as long as the motion continues, but ceasing when that ceases."

Faraday modified the essential elements, substituting wire loops for the disk, electromagnets with and without cores, disks of different metals, etc. The revolving loop showed an alternating current, whereupon Faraday rectified the current by a true commutator. He now had all the essential elements of a practical dc generator. The Jan-



USING the great horseshoe magnet of the Royal Society, Faraday revolved a copper disk at the poles and first generated a continuous electric current.

uary 1832 issue of the *Philosophical Transactions of the Royal Society* carried the first of Faraday's 29 papers on his electrical research.

The discovery of electromagnetic induction led to other important electrical developments, including recognition of self-induced current, polarity in diamagnetic bodies, lines and fields of magnetic force, and the use of induced current as a measure of field intensity. Advances in the field of electrochemistry followed, including the annunciation of Faraday's law of electrochemical decomposition, analysis of electric generation in the voltaic pile, and the general theory of electrolysis. He introduced new terms such as electrode, electrolyte, electrolysis, anode, cathode, ion, anion, and cation; the new vocabulary indicated Faraday's expansion into other fields of science.

Faraday established "specific inductive capacity" by comparing the dielectric properties of oil, sulfur, shellac, and glass with those of air. As a result of this contribution, the International Electrical Commission, at its meeting in Paris in 1891, termed the electrical unit of capacitance the *farad*. A second unit, honoring Faraday's contributions to electrochemistry, is the *faraday*; it represents the amount of electric charge carried by one gram-molecule of an ionized substance. Thus, Faraday has the rare distinction of having two units named for him.

Faraday's Bakerian lecture at the Royal Society in 1856 was his last contribution to that body. He held his final Friday night discourse at the Royal Institution in June 1862 and the final entry in his experimental notebook concerned the effects of magnetism upon a beam of light, although the instruments were too crude to be effective. (Zeeman was successful 35 years later and was awarded the Nobel Prize for this observation.) In 1865 Faraday transferred the directorship of research at the Royal Institution to his friend, Dr. John Tyndall. For his final years Queen Victoria offered a house at Hampton Court to be used by the Faradays as long as they lived; to this, after 1862, they retired. His eyes were finally closed there on August 25, 1867.

The heritage

Beyond the limitations of mathematical analysis of which he was capable, Faraday's experimental approach and intuitive resolutions opened channels of inquiry into which the Thomsons and Maxwells moved. He had written: "Nothing is so good as an experiment which, whilst it sets error right, gives an absolute advancement in knowledge." His concern, in his more mature years, with the universal forces of attraction were well analyzed in a recent biography by L. Pearce Williams. Faraday's concept of the line of force was "the physical line across the gulf that separated action-at-a-distance physics from field physics." Few of his contemporaries shared Faraday's notions of the line of force but staunch support was accorded it by Maxwell, whose paper, given before the Cambridge Philosophical Society in 1855, bore the title "On Faraday's Lines of Force," and in which he acknowledged his debt to Faraday. Two years later, in a long letter to Faraday, Maxwell wrote: "Now as far as I know you are the first person in whom the idea of bodies acting at a distance by throwing the surrounding medium into a state of constraint has risen, as a principle to be actually believed in." In the following two decades Maxwell developed the concept of field theory as the proper representation of electromagnetism.

Little could Faraday have dreamed, during his lifetime, of the vast and beneficent forces that his work was to bequeath to man.